The Effect of Narrowband and Wideband Interference on the BER of MB-OFDM UWB Links
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I. Abstract

This work is an exploration of the impact of interferers on an ultrawideband (UWB) transmitter-receiver link. Both narrowband and wideband (specifically, UWB) interference is considered. Two physical layer models are built and simulated. The performance metric is the link’s bit error rate (BER). For both the narrowband and UWB interferer models, the dependence of the BER on the power of the interferer is presented. For the narrowband interferer case, the impact of the relative placement of the signal within the UWB link’s spectrum is simulated and discussed. Similarly for the UWB interferer, the time-frequency code (TFC) is varied to quantify the effect of spectrum overlap between co-located UWB networks on BER.

II. Introduction

Ultrawideband (UWB) Personal Area Networks (PANs) have the potential to offer very high data rates over short distances by evenly spreading information over a very wide bandwidth, making it appear as noise. The allure of UWB-enabled products is data rates upwards of 480Mbps at low power. At those data rates it is possible to wirelessly send high bandwidth signals such as high-definition video. This “noise” of the UWB signal must co-exist with other radio signals that may occupy the same spectrum, whether they are other wideband sources, or narrowband sources. The impact of interference on the performance of a PAN is an area of active research. Concern for the impact of interference between co-located PANs using UWB have motivated some researchers to propose improved MAC protocols relative to what is specified in the ECMA-368 standard.

The proposal for an improved MAC, called Interference Management Distributed Reservation Protocol (IM-DRP), allows transmitters and receivers to intelligently choose medium access slots (MASs) that are not being used by neighboring PANs and thereby reduce the impact of interference and improve overall throughput. [1], [2] The authors considered cases where there are a fairly large number of nodes (20 to 80) that are co-located to emphasize the impact of interference. The ECMA-368 standard specifies that UWB links use multi-band orthogonal frequency division multiplexing (MB-OFDM) at their physical layer. The standard says that each link uses a particular time-frequency code (TFC) which specifies a sequence of sub-bands within the UWB spectrum that the link uses in a cyclical fashion. Channels within a band are created by these TFCs because the time-interleaving nature of the TFC allows for some separation in the spectrum usage in time. However, the separation is not perfect and within the set of all TFCs it is possible for two different TFCs to use the same spectrum for 1/3 of the time. The assumption underlying the development of the IM-DRP is that when 2 different UWB links using different TFCs happen to be using the same spectrum, the interference adversely impacts throughput. This work will quantify that impact in terms of BER.

In addition, this work will explore through simulation the impact of narrowband interference on a UWB link. The motivation here is that an imagined UWB PAN is deployed in a home and will have to co-exist with other narrowband radio equipment, such as wireless local area networks (WLANs). In 2002, the FCC specified that the spectrum from 3.1GHz to 10.6GHz may be used for UWB communications as long as the equivalent isotropically radiated power remains below roughly –41dBm/MHz. In the WLAN space, most of the currently popular flavors of the IEEE 802.11 standard operate in the ISM band around 2.4GHz, but the 802.11a and 802.11n standards may operate around 5GHz, which falls in the spectrum range allocated for UWB. The wide spectrum range allowed for UWB is already used by many other radio technologies. The potential for interference between UWB devices and the many 802.11 products already
operating in so many homes is imminent and worth some further study. That is the motivation behind the simulation model which introduces narrowband interference to the UWB link.

### III. UWB link with Narrowband Interferer Model

The model of the UWB link with a narrowband (NB) interferer is shown in Diagram 1. Like all the models and simulation in this work, it was constructed with Matlab/Simulink software. The code base for the TX-RX pair was made freely available by the authors in [3]. It is similar to the physical layer model of the 802.11 demo in the Communications blockset for Matlab/Simulink, but the authors of [3] tailored the design to the UWB physical layer and created various user-selectable channel models. This work adds to those models both narrowband and wideband interference models which were then simulated to quantify their impact on the link’s BER. In Diagram 1, the output of the red ‘NB interferer’ is added to the output of the UWB transmitter block, and the sum is passed through the UWB channel, and then received by the UWB receiver block. The interferer can be disabled or enabled by switching the manual switch between 0 and 1, respectively. The narrowband interferer has a data bandwidth of roughly 30MHz which is intended to be comparable to the 20MHz bandwidth of 802.11 standards. The power level of the NB interferer is user-selectable and swept to study its impact on the UWB link’s BER. The frequency offset of the NB interferer is also variable with respect to the center frequency of the UWB signal, and its value is also swept to study its impact on the BER.

![Diagram 1. Model of TX-RX UWB link with narrowband (802.11) interferer](image)

The implementations of the UWB transmitter, UWB channel, UWB receiver, and the NB interferer are shown in Diagrams 2, 3, 4, and 5, respectively. In Diagram 2, the information source is a random binary source so the full bandwidth of the UWB spectrum will be filled. The information source is encoded and punctured with a convolutional code; the result is interleaved and then modulated with QPSK, which is
specified in the standard. The OFDM transmitter block takes care of the spreading, pilot-insertion, channel-estimate sequence insertion, and zero-padding prior to the IFFT operation. After the IFFT operation, the sequences needed for frame synchronization and the guard periods are inserted in the signal. In the Frequency Hopping and Filtering block, the signal is upsampled by 6, filtered to meet the FCC spectral mask requirements for UWB and then shifted in frequency by the current value of the TFC code. The TFC codes progress through a repetitive sequence of frequency offsets, which place the center frequency of the UWB transmission at multiples of 528MHz offsets. The TX transmits at that offset for a finite duration of time and then switches to the next offset; this behavior is made clear in the spectrogram plots that follow. The signal to noise ratio (Es/No) of the channel was set to 60dB, which is likely too high to be rooted in physical reality. This was done to minimize the impact of the channel noise on the radio link and accentuate how the interferer impacts the link’s BER. The channel model was implemented as a filter with a response shown in the right-hand side of Diagram 3, with the addition of additive white Gaussian noise. The delay spread and SNR of the channel were kept constant for all the simulation results in this work. The NB interferer model is shown in Diagram 5; it too uses a random information source to spread energy over its entire bandwidth. The modulation scheme is 16-QAM, the upsampling is achieved with a root-raised cosine filter and the bandwidth is limited by a LPF to give the signal some semblance of a real 802.11 signal that would adhere to the FCC emission spectral mask requirement. The exact location of the interferer in frequency space is determined by the parameter ‘Int_freq_offset’, and the final block is a gain block that sets the interferer’s power level.

Diagram 2. MB-OFDM physical layer transmitter model

Diagram 3. UWB channel model used throughout this work
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Diagram 4. MB-OFDM physical layer receiver model

Diagram 5. Narrowband interferer model creates 16-QAM with BW≈30MHz at any frequency offset and power level

IV. Simulation Results – the impact of NB Interference on the UWB link

In Figure 1 the power-spectral density (PSD) and the spectrogram of the transmitted signal is shown. On the left side, the interferer is off, and the transmitted spectrum is flat with a bandwidth ~3*528MHz = 1584MHz. The band is split into 3 sub-bands each with bandwidth of 528MHz, and in the spectrogram plot one can see how the time-frequency interleaving is achieved by only using one of the 528MHz sub-bands at a time. In the spectrogram, the x-axis represents time, the y-axis represents frequency, and the colors indicate the power of the signal at that particular time and frequency with the red colors indicating high power, and blue colors indicating low power. The simulation results on the right side of Figure 1 show that the NB interferer has been turned on and is added to the UWB signal. The red PSD is the sum of the signal and interferer, and the blue PSD is the NB interferer only. The power level of the interferer was set to –60dBm. In the spectrogram, the NB interferer appears as a consistent red horizontal streak at an offset of 100MHz from the center of the UWB spectrum.

The received symbol constellation and the BER of the simulation are shown for the NB interferer on and off in Figure 2. For all simulations, the simulation was terminated when the number of bits received exceeded 10kbits. This limits the minimum bound of the BER measurement. If one would like to increase the resolution of the BER measurement, the maximum number of received bits could be increased accordingly with the understanding that the computation duration of the simulation would also increase. For no interference on the left-hand side, the constellation the symbols fall neatly into 4 separable groupings and the resulting BER is 0. For the added NB interference on the right-hand side, the constellation shows points falling mostly in the 4 groupings but there are some outliers that fall on boundaries in the symbol space; as a result the BER increases to 1.5e-3 due to the interference.
Figure 1. (Left) Transmitted signal's PSD (red) and spectrogram when the NB interferer is OFF; (Right) Transmitted signal's PSD (red) and interferer's PSD (blue) and spectrogram when the NB interferer is ON with offset=100MHz and power=-60dBm

Figure 2. (Left) Received constellation (post-equalization) and BER with interferer OFF; (Right) Received constellation (post-equalization) and BER with interferer ON
The impact of the NB interferer’s power and placement in the frequency space on the BER is shown in figures 3 and 4, respectively. In Figure 3, the BER drops off sharply as the NB interferer’s power is lowered below –40dBm/Hz. In addition, if the interferer power is above –25dBm/Hz, the throughput on the UWB communication link is reduced to 0bps as the BER reaches 0.5, indicating that every other bit is received incorrectly. This data indicates that NB interferers pose a threat to UWB links if the NB power is above a certain threshold. Below that threshold, there is a favorable increase in the UWB link’s BER as the NB interferer’s power is lowered. This data could be used to predict the power specifications for a co-located 802.11 network and a UWB link that overlap in their spectrum usage. The specification for 802.11 maximum transmission power is 20dBm for the entire signal (20MHz), which is a PSD of –53dBm/Hz. The simulation data shows that at –53dBm/Hz the BER is on the order of 1e-2, which is non-negligible. To circumvent problems arising from the interference of the UWB and NB source, the interferer’s power may need to be reduced or moved out of the UWB’s spectrum.

The simulation results in Figure 4 show that there is sensitivity to exactly where the NB interferer transmits within the UWB spectrum. The x-axis represents the offset in MHz from the center of the transmitted UWB spectrum where the NB interferer transmits its 30MHz signal. This is an unexpected result as the UWB PSD is theoretically flat over frequency and the location of the NB interference should therefore impact the link equally. One possible explanation is that the delay spread of the channel model affects the NB interferer differently at different points in the spectrum and gives rise to this result. Further work needs to be done to understand this effect.

![UWB BER vs. NB Interferer Power (offset=100MHz)](image)

Figure 3. UWB BER for varied NB interferer power levels showing saturation of BER=0.5 for power above -25dBm
Figure 4. Link BER vs. NB interferer placement within the UWB spectrum

V. UWB link with UWB Interferer Model

The top-level model of the UWB link with the WB interferer, shown in Diagram 6, is identical to the NB interferer case, except the red interferer block is a replica of the UWB transmitter with some modifications. A notable modification is shown in Diagram 7 where the frequency offset calculation takes as parameter ‘Int_TFC*uwb.W’; this allows the user to change the TFC of the interferer to any sequence. For all the simulation results in this work the TFC of the signal is 1, and the TFC of the interfering UWB transmitter is varied 1-7.
VI. Simulation Results – the impact of WB interference on the UWB link

Figure 5 shows the PSD of the WB interferer (blue) and the sum of the signal and interferer (red) for the simulation. Now both the interference and the signal occupy ~1.5GHz. The relative power of the interference with respect to the signal is a variable set by the user, and in this case the interference is −3dB below the signal. This is a reasonable assumption if the source of the interference is farther away from the receiver than the intended signal’s transmitter. Similarly, if the interferer is located closer to the receiver than the signal’s transmitter, it is possible for the interference to be stronger in power than the signal. This case is considered as well in the simulations that follow.
The first parameter varied was the interferer’s TFC and simulation results are shown in Figure 6. In both cases, left-side and right-side, the interferer’s power was -3dB relative to the signal’s power. On the left side, the TFC was 1 for both the interferer and the signal. As a result, the spectrogram shows that the high energy areas appear in the same pattern as if only the signal was transmitting because the sub-band’s spectrum used fall on top of each other in time. In the symbol constellation space there is additional groupings caused by the interferers and the equalizer helps to keep interferer’s symbols grouped together, but grouped outside of the signals symbols. As a result, the BER is 0. On the right side, the TFC of the interferer was changed to 2, and the signal was kept at 1. In the spectrogram, the pattern is different because for 2 out of the 3 time slots, the interferer and signal are transmitting over different sub-bands. For 1 out of the 3 time slots, the interferer and signal are transmitting over the same sub-band. In the symbol constellation space, the result is that there are outliers between the symbol groupings caused by the interference. However, the outliers are orthogonal to the true signals and the signal symbols remain separable and identifiable, so the BER is 0.

Simulation results from a sweep of the relative power of the interferer are shown in Figure 7. The interesting result here is that if the interferer power is below 1dB relative to the signal power, the interferer has no negative impact on the BER of the link. This result indicates that for co-located PANs a viable solution to interference between links using different TFCs is simply to reduce the power of the interferer such that at the receiver the interfering power stays below the intended transmitter’s. This is an alternative approach to the IM-DRP MAC, and could be implemented across the MAC and PHY layer boundary without any change to the MAC specified in the ECMA-368. Along those same lines, the interferer’s TFC code was changed to all values 1-7 for relative power levels of -2dB, 0dB, and +2dB, and the BER results are plotted in Figure 9; the spectrograms and BERs for the +2dB case are shown in Figure 8. The results show that if the interferer’s power is less than -2dB of the signal’s power, the interference has no negative impact on the link (BER remains 0) for all values of TFC. If the interferer happens to have larger power than the signal, then it is possible to choose a TFC that has a better BER than other TFCs. Overall the simulation data indicates that if the interferer level can be kept below the intended signal’s power level, the UWB link does not suffer BER degradation from the WB interference.

Figure 5. Transmitted signal PSD showing UWB BW-1.5GHz, blue is the UWB interferer at -3dB below the signal, and red is the sum of the interferer and the signal

![Image of transmitted signal PSD with UWB BW-1.5GHz, showing blue as the UWB interferer at -3dB below the signal, and red as the sum of the interferer and the signal.](image-url)
Figure 6. (Both sides) Interferer power is -3dB to signal power; (Left) Both interferer and signal link use TFC=1; (Right) interferer uses TFC=2 while signal remains at TFC=1
Figure 7. Link BER vs. WB interferer relative power to signal when signal uses TFC=1 and interferer uses TFC=2

Figure 8. Spectrogram and BER for interferer set to every TFC (1..7) (signal TFC=1) with interferer power 2dB greater than signal
The impact of NB and WB interference on a UWB link has been simulated and the results discussed. The motivation was to quantify the assumed problems caused by interference that are addressed by the interference management DRP offered by the work in [1] and [2]. In addition, the motivation was to check the impact of NB interference on a UWB link in an imagined scenario where there is a 802.11 radio operating in the vicinity of a UWB link. The simulation results showed that NB interference is a potential threat to the BER of a UWB link, even at the –53dBm/Hz maximum levels allowed by the 802.11 standard. The straightforward solution to mitigate the threat is to move the NB interferer below the 3.1GHz minimum frequency of UWB or to lower the NB signal’s power. The simulation data shows UWB interference is also a potential problem for co-located UWB PANs, so the authors of [1] and [2] have valid concern. The simulation data says that if a WB interferer’s power level is greater than +1dB of the signal’s power level, there is degradation of the link’s BER for certain TFCs. The objective of this work was to quantify the impact of NB and WB interference on a UWB link and that objective was achieved through modeling and simulation. The next logical step in this work would be to perform measurements to support the validity of the models, or call for the modification of the models to more accurately predict real measurement.

Figure 9. Link BER over WB interferer’s TFC (signal TFC=1) for 3 relative powers of interfer: +2dB, 0dB, -2dB relative to signal

VII. Conclusions
VIII. References


IX. Appendix

TFC codes and their sequences:

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(a) band group 1.